Advanced Encryption Approaches for Machine-to-Machine Communications and Big Data Processing

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Roadmap

- Introduction
- Certain Security Challenges: Minimization of the Security Overheads
- Illustrative Technical results: Towards Advanced Lightweight Security Mechanisms

1. Introduction

Our Topic, Challenges and Messages

Our Topic: IoT and Big Data

Our Topic: IoT & M2M Communications

Our Topic:

M2M Is All About Real-Time "Big" Data

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http://strata.oreilly.com/2012/01/what-is-big-data.html

Challenges

- Current information-communication technologies (ICT) heavily involve machine-to-machine (M2M) communications and big data processing.
- These two issues open a number of mathematical challenges regarding data privacy and secrecy.
- A particular challenge is developing of algorithms which support reduction of the overheads implied by employed techniques for data security. Frequent employment of the security mechanisms could result into a heavy cumulative overhead regarding implementation complexity, computational complexity and power consumption.
- At the same time we face a request for a high and preferably provable security of the employed cryptographic techniques.

Main Messages

- Accordingly, the advanced cryptographic techniques should at the same time provide **high security and as small as possible overheads to the main functionality of a system**.
- This talk considers elements of an encryption approach for fulfilling the claimed goals based on **involvement elements of coding theory into traditional compact cryptographic techniques for encryption** in order to provide a secure and lightweight processing of data for the privacy and secrecy purposes.

- We point out to certain elements from **coding theory** which shows that **joint employment of pseudo-randomness generated by compact finite-state machines, randomness and dedicated coding provide a framework for developing of lightweight and provable secure encryption algorithms for data privacy and secrecy.**

2. Certain Security Challenges

Minimization of the Overheads
Implied by Security Mechanisms

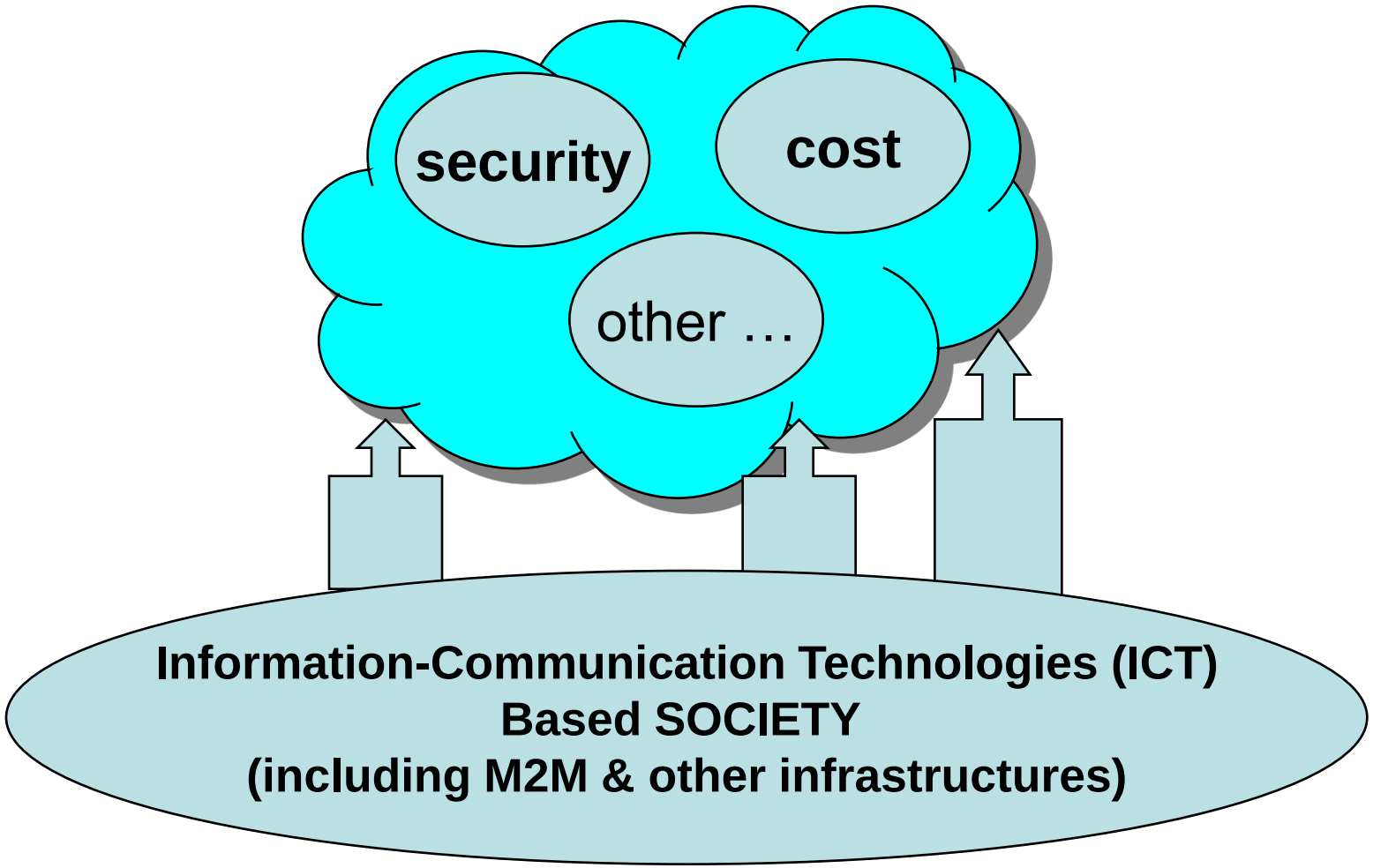
IoT Atributi

Security – The Key Issue of IoT

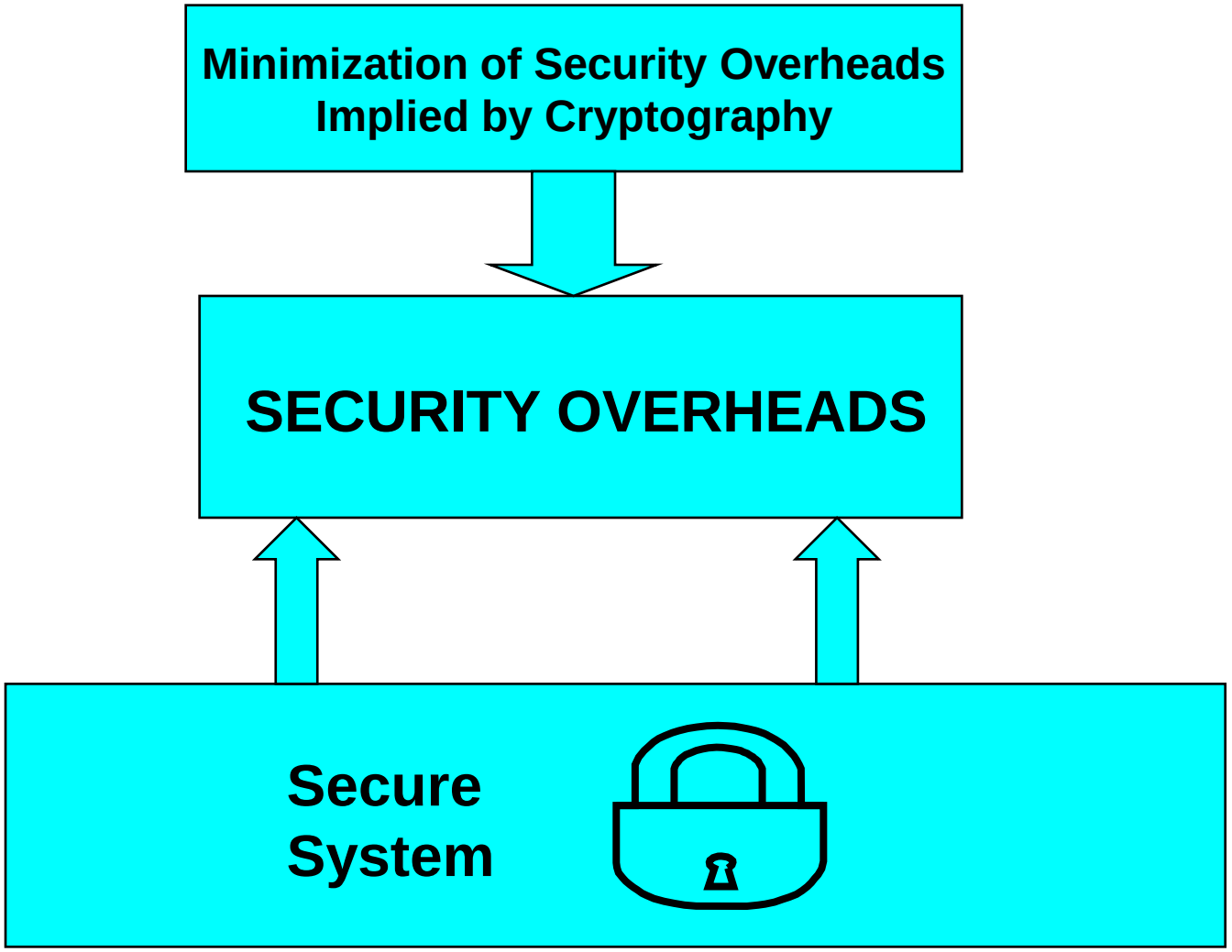
Certain Challenges of Cyber-Security

- **Security evaluation of the components and basic lightweight cryptographic algorithms**
- **Design** of advanced lightweight cryptographic algorithms which provide **provable security and low implementation overheads**

IoT Concerns



Minimization of the Security Costs



Minimization of the Overheads Implied by Security Mechanisms

- minimization of the implementation overheads
- minimization of the computational overheads (and particularly: minimization of the key management, authentication and encryption overheads)
- minimization of the communications overheads
- minimization of power-consumption

Trends & Implications

- **Extensive employment of cyber-security mechanisms**
- **Overheads to the main functionality implied by employed security mechanisms**

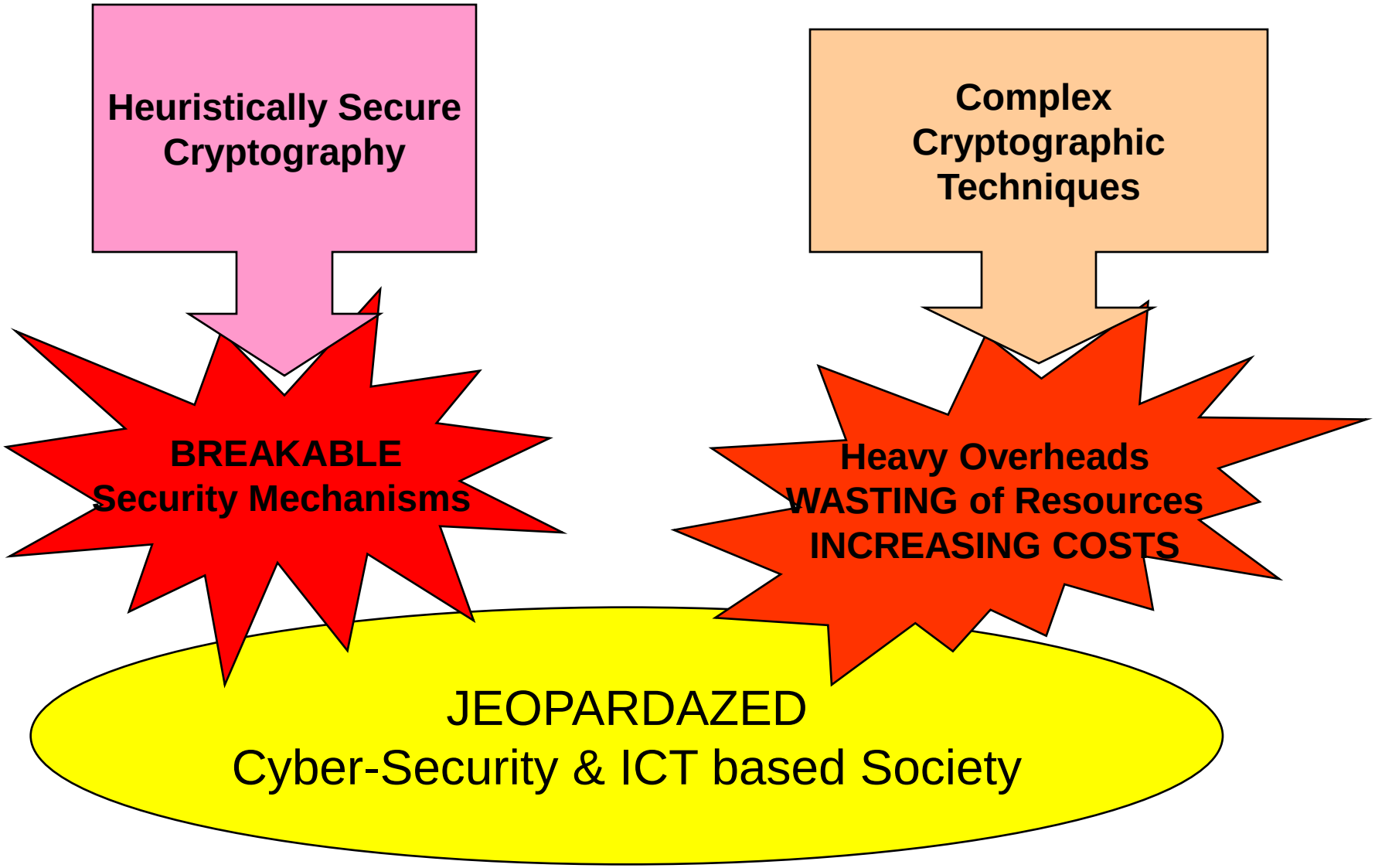
Cryptographic Challenges

Provable Security of employed security mechanisms

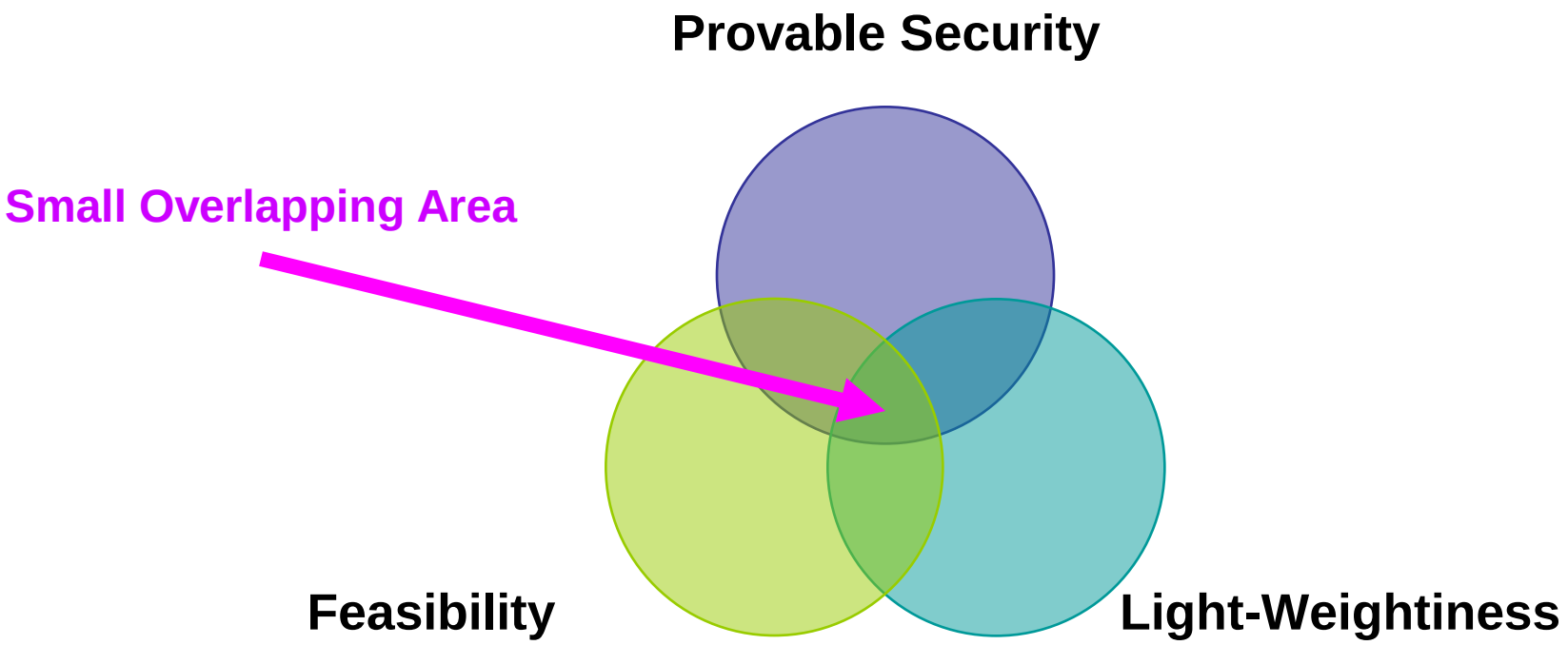
Provable Secure means that breaking is as hard as solving a hard mathematical problem

Minimization of the overheads implied by the security mechanisms

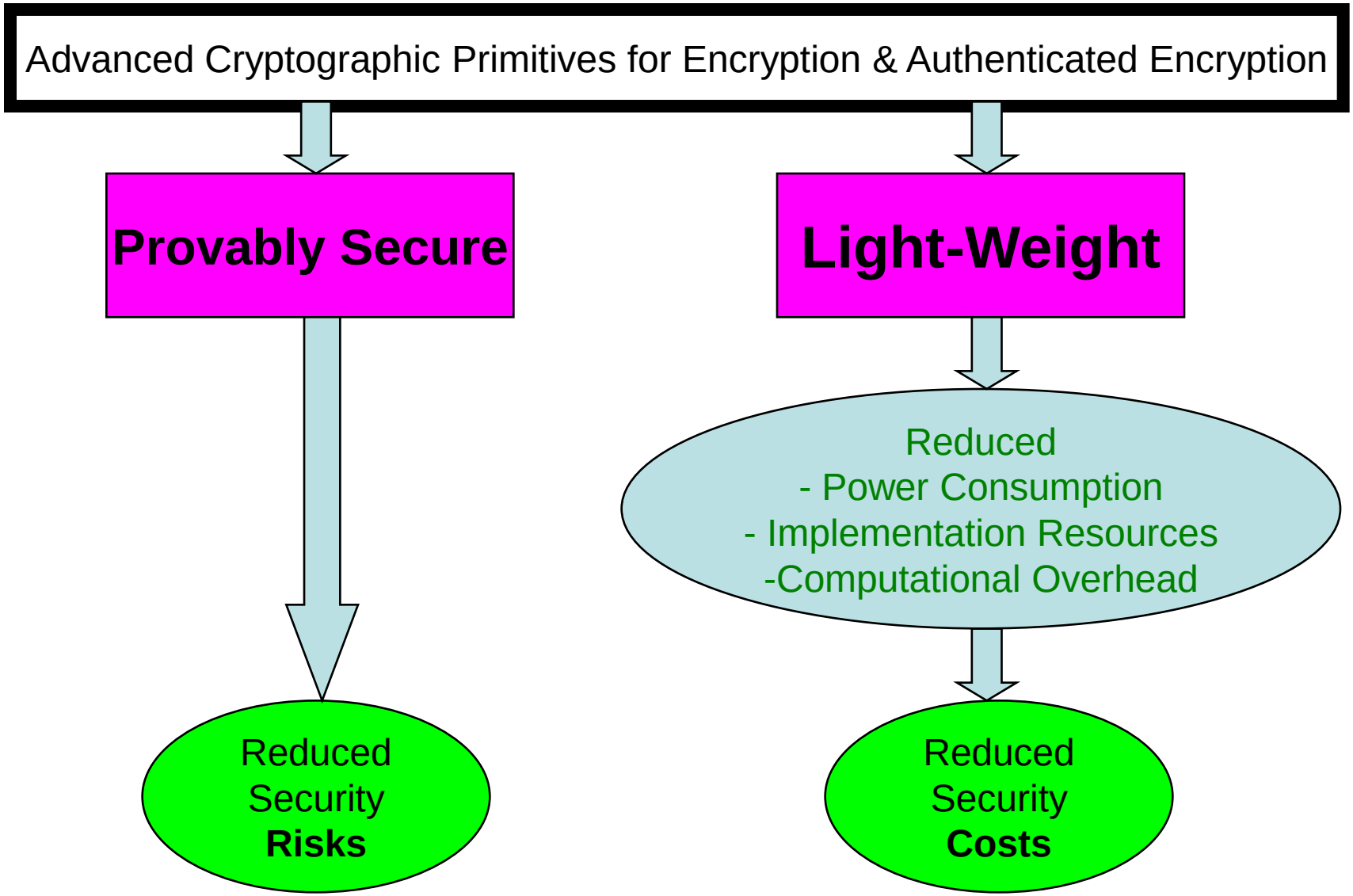
Potential Disastrous Impacts



Cryptographic Challenges regarding Cryptographic Primitives



Particular Goals of the Advanced Construction



3. Illustrative Technical Issues

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Advanced Approach Against Existing Ones

- Practical light-weight cryptographic primitives based on **randomized algorithms**.
- Randomization provides framework for **provable security**.

- Traditional light-weight cryptographic primitives are based on **deterministic** algorithms.
- Security is based on the **heuristics** and the “expected” **computational complexity** arguments.

Security Evaluation / Cryptanalysis

- **Security evaluation / cryptanalysis of particular lightweight symmetric-key cryptographic techniques** for application in critical infrastructures
- Developing of **generic techniques for security evaluation / cryptanalysis** of certain classes of symmetric-key encryption and authentication schemes

Illustrative Technical Issues on Advanced Lightweight Encryption

3.1 Illustrative Technical Result I

The LPN Problem Based Security

Definition: LPN Search Problem. Let s be a random binary string of length l. We consider the Bernoulli distribution $\mathcal{B}_\theta$ with parameter $\theta \in (0, 1/2)$. Let $\mathcal{Q}_{s,\theta}$ be the following distribution:

$$\{(a, < s, a > \oplus e) | \leftarrow \{0,1\}^l, e \leftarrow \mathcal{B}_\theta\} .$$

For an adversary $\mathcal{A}$ trying to discover the random string s, we define its advantage as

$$\mathsf{Adv}_{\mathsf{LPN}_{\theta,\mathcal{A}}}(l) = \Pr[\mathcal{A}^{\mathcal{Q}_{s,\theta}} = s | s \leftarrow \{0,1\}^l] .$$

The LPN_θ problem with parameter θ is hard if the advantage of adversaries $\mathcal{A}$ that make a polynomial number of oracle queries is negligible.

Definition: LPNDP - LPN Decisional (Distingushing) Problem. Let s, a be binary strings of length l. Let further $\mathcal{Q}_{s,\theta}$ be as in Definition of the LPN search problem. Let $\mathcal{A}$ be a adversary. The distinguishing-advantage of $\mathcal{A}$ between $\mathcal{Q}_{s,\theta}$ and the uniform distribution $\mathcal{U}_{l+1}$ is defined as

$$\mathsf{Adv}_{\mathsf{LPNDP}_{\theta,\mathcal{A}}}(l) = \mathsf{Pr}[\mathcal{A}^{\mathcal{Q}_{s,\theta}} = s | s \leftarrow \{0,1\}^l] - \mathsf{Pr}[\mathcal{A}^{\mathcal{U}_{l+1}} = 1] \; .$$

The LPNDP_θ with parameter θ is hard if the advantage of adversaries $\mathcal{A}$ is negligible.

It has been shown that the distinguishing-problem is as hard as the search-problem with similar parameters.

Underlying Problem of the LPN

(on hardness of solving an over-defined system of N probabilistic equations with K unknown variables)

Complexity of the problem strongly depends on the parameters K, N and the corruption noise

noisy variables

OVERDEFINED SYSTEM

linear-f1(x_1, x_2, …, x_K) = z_1

linear-f2(x_1, x_2, …, x_K) = z_2

⋮

linear-fN(x_1, x_2, …, x_K) = z_N

Left-hand side of the system Is "available" only after a binary symmetric channel with known probability of errors

K << N

Definition 1. Let $\mathbf{S}$ be a secret $k \times n$ binary matrix, and $\mathbf{P}_0$ be a secret $n \times n$ secret permutation matrix. Let $\mathbf{a}_t$ be a k-dimensional random vector which is publicly available, $t = 1, 2, ...$ Finally, let $\mathbf{P}_t = f(\mathbf{a_t}, \mathbf{P}_{t-1})$, where $f(\cdot)$ is a suitably selected function. For $t = 1, 2, ...,$ encryption of $\mathbf{x}_t$ into $\mathbf{z}_t$ is

$$\mathbf{z}_t = (C(\mathbf{x}_t)||\vec{\rho_t})\mathbf{P}_t \oplus \mathbf{a}_t \cdot \mathbf{S} \oplus \vec{\nu_t} \ ,$$

and accordingly, decryption of $\mathbf{z}_t$ into $\mathbf{x}_t$ is as follows:

$$\mathbf{x}_t = C^{-1}(tcat_m((\mathbf{z}_t \oplus \mathbf{a}_t \cdot \mathbf{S})\mathbf{P}_t^{-1}) \ .$$

Theorem. Assume there is an adversary $\mathcal{A}$, running in time T , and attacking the stream cipher specified by Definition 1 with parameters (ℓ, m, k, n, η) in the sense of IND-P1-C0 with advantage δ by making at most q queries to the encryption oracle. Then there is an algorithm $\mathcal{M}$ making $O(q)$ oracle queries, running in time $O(T)$, and such that

$$\left|\mathsf{Pr}\left[\mathrm{s} \leftarrow \{0,1\}^k \ : \ \mathcal{M}^{\Pi_{s,\eta}}(1^k) = 1\right] - \mathsf{Pr}\left[\mathcal{M}^{\mathcal{U}_{k+1}}(1^k) = 1\right]\right| \geq \frac{\delta}{n} \, .$$

What the theorem tell us?

- The theorem tell us that if we can “break” the encryption scheme in the sense of the distinguishability, than we can solve a related decisional LPN problem.

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3.2 Illustrative Technical Result II

Information-Theoretic Security

Significance of Information-Theoretic Security Evaluation

- Information-theoretic security evaluation tell us about a **residual uncertainty (the equivocation)** of unique recovering the secret elements even with unlimited computational power.
- Note that even if, after all, the residual uncertainty does not exist, i.e. the equivocation is zero, **the underlying computational problem could be a very complex one**.

Algebraic Representation of Encryption - Linear Codes are Employed

$$C_H(\mathbf{a}||\mathbf{u}) = [\mathbf{a}||\mathbf{u}]\mathbf{G}_H, \tag{1}$$

and $\mathbf{G}_H$ is an $m \times m$ matrix, and thus

$$\begin{aligned} C_{ECC}(C_H(\mathbf{a}||\mathbf{u})) &= C_{ECC}([\mathbf{a}||\mathbf{u}]\mathbf{G}_H) \\ &= [\mathbf{a}||\mathbf{u}]\mathbf{G}_H\mathbf{G}_{ECC} \\ &= [\mathbf{a}||\mathbf{u}]\mathbf{G} \end{aligned} \tag{2}$$

where $\mathbf{G}_{ECC}$ is an $m \times n$ binary generator matrix corresponding to $C_{ECC}(\cdot)$, and $\mathbf{G} = \mathbf{G}_H\mathbf{G}_{ECC}$ is an $m \times n$ binary matrix summarizing the two successive encodings at the encryption side, implying that

$$\mathbf{z} = [\mathbf{a}||\mathbf{u}]\mathbf{G} \oplus \mathbf{x} \oplus \mathbf{v}\ . \tag{3}$$

Lemma 1. When $H(\mathbf{X}^n) = n \geq H(\mathbf{U}^{m-\ell}) + H(\mathbf{V}^n)$, the equivocation of the keystream output knowing the plaintext and the received signal fulfills the following tight lower bound:

$$H(\mathbf{X}^n|\mathbf{A}^l, \mathbf{Z}^n) \geq H(\mathbf{U}^{m-l}) + H(\mathbf{V}^n) - \delta(C_{ECC}) \ ,$$

where for a given positive $\epsilon \rightarrow 0$

$$\delta(C_{ECC}) = H(\epsilon) + \epsilon \log(2^{m-l} - 1) \rightarrow 0 \ .$$

Theorem 1. Let $H^*(\mathbf{K}|\mathbf{A}^{\tau l}, \mathbf{Z}^{\tau n})$ denote $H(\cdot)$ in the special case when $m = l$, i.e. when the pure random bits are not involved. When $\mathsf{Pr}(V_i^{(j)} = 0) = 1 - \mathsf{Pr}(V_i^{(j)} = 1) = 1 - p > 1/2$, $i = 1, 2, ..., n$, $j = 1, 2, ..., \tau$, we have

$$H(\mathbf{K}|\mathbf{A}^{\tau l}, \mathbf{Z}^{\tau n}) - H^*(\mathbf{K}|\mathbf{A}^{\tau l}, \mathbf{Z}^{\tau n}) = H(\mathbf{U}^{\tau(m-l)}|\mathbf{A}^{\tau l}, \mathbf{Z}^{\tau n}) - H(\mathbf{U}^{\tau(m-l)}|\mathbf{A}^{\tau l}, \mathbf{K}, \mathbf{Z}^{\tau n}) ,$$

and there exists a threshold τ_{thres} such that

$$H(\mathbf{K}|\mathbf{A}^{\tau l}, \mathbf{Z}^{\tau n}) \begin{cases} > 0 & \text{for} \quad \tau < \tau_{thres} \\ \to 0 & \text{for} \quad \tau \geq \tau_{thres} , \end{cases}$$

assuming that $n \leq |\mathbf{K}| \ll \tau_{thres} n$, and $\tau_{thres} np \ll \tau_{thres} n/2$.

Implications of Lemma 1 and Theorem 1

- Lemma 1 justifies that the **considered encryption model provides a certain level of the posterior uncertainty about its secret elements (i.e., positive equivocation)** assuming that the sample for cryptanalysis is (very) short.
- Theorem 1 shows that **this positive equivocation cannot be preserved, when the sample for cryptanalysis increases**, and that it tends to zero assuming a large enough sample implying that the uncertainty about the secret key employed in the keystream generator tends to zero, i.e., it can be correctly recovered by **(potentially hard)** computational efforts.

3.3 Illustrative Technical Result III

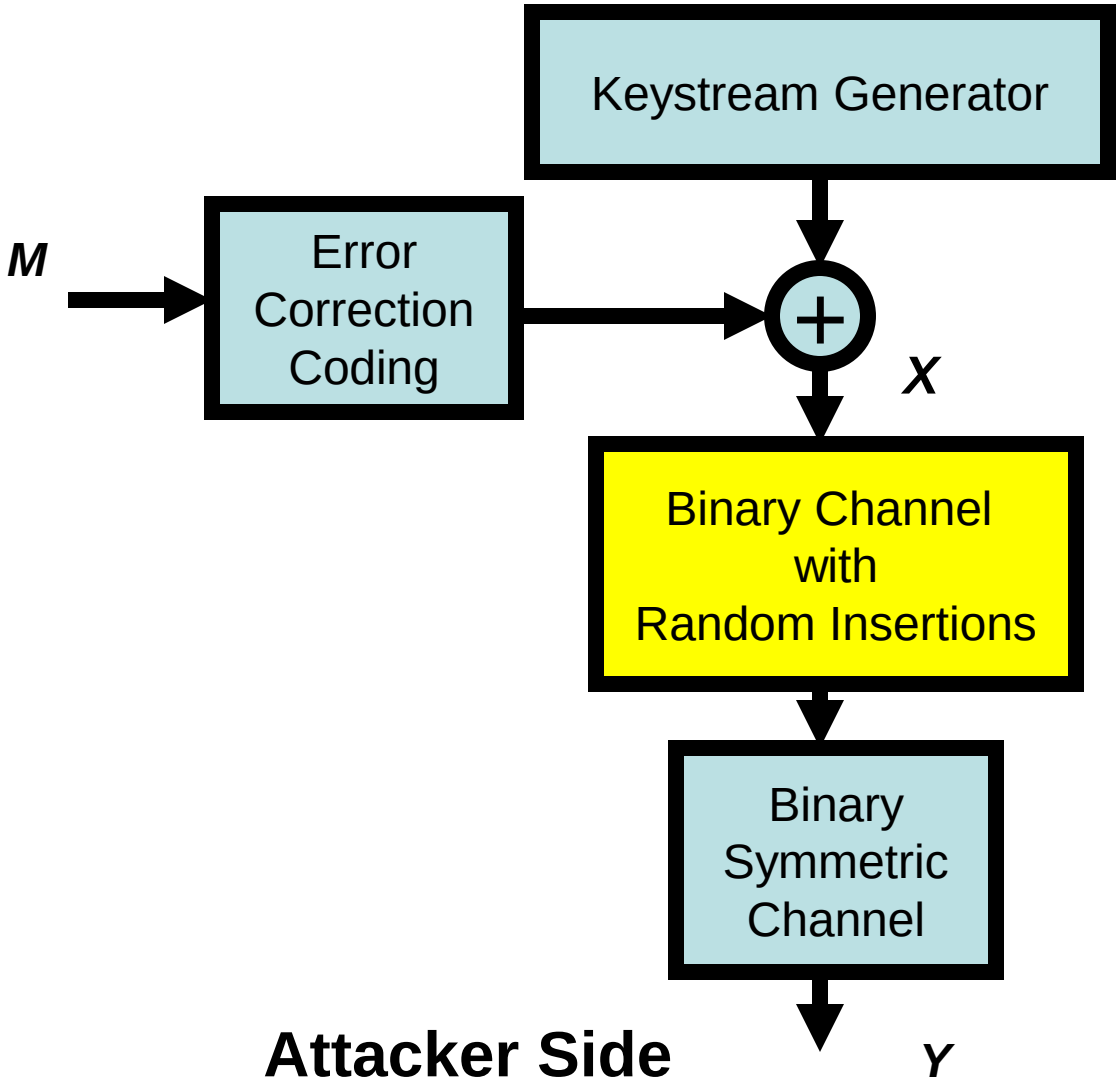
Effect of Channels with
Synchronization Errors

Underlying Idea for Security Enhancement

- **Make the channel toward the Attacker "more noisy".**

- Instead that an Attacker faces Binary Symmetric Channel, enforce that the Attacker faces a **binary channel with insertions and complementations**.

Framework Model for the Security Enhancement: the Model an Attacker's have to Face



Definition 1: The Adversarial Indistinguishability Experiment. consists of the following steps:

1. The adversary $\mathcal{A}$ chooses a pair of messages $(\mathbf{m}_0; \mathbf{m}_1)$ of the same length n, and passes them on to the encryption system for encrypting.

2. A bit $b \in \{0,1\}$ is chosen uniformly at random, and only one the two messages $(\mathbf{m}_0; \mathbf{m}_1)$, precisely $\mathbf{m}_b$, is encrypted into ciphertext $\text{Enc}(\mathbf{m}_b)$ and returned to $\mathcal{A}$;

3. Upon observing $\text{Enc}(\mathbf{m}_b)$, and without knowledge of b, the adversary $\mathcal{A}$ outputs a bit b_0;

4. The experiment output is defined to be 1 if $b_0 = b$, and 0 otherwise; if the experiment output is 1, denoted shortly as the event $(\mathcal{A} \to 1)$, we say that $\mathcal{A}$ has succeeded.

Definition 2. An encryption scheme provides indistinguishable encryptions in the presence of an eavesdropper, if for all probabilistic polynomial-time adversaries $\mathcal{A}$

$$\mathsf{Pr}[\mathcal{A} \to 1 | \mathsf{Enc}(\mathbf{m}_b)] \leq \frac{1}{2} + \epsilon \,,$$

where $\epsilon = \mathsf{negl}(n)$ is a negligibly small function.

Theorem: Let the encrypted mapping of M^n into X^n be such that $\frac{1}{2}+\epsilon$ equals the advantage of the adversary $\mathcal{A}$ (specified by Definition 2) to win the indistinguishability game (specified by Definition 1), and let the mutual information $\mathcal{I}_{iud}(X;Y)$ be known. Under these assumptions, for large n,

$$\Pr[\mathcal{A} \to 1 | Y^{(n)} = \mathbf{y}] = \frac{1}{2} + \epsilon \cdot \delta, \quad \text{where}$$

$$\delta < \mathcal{I}_{iud}(X;Y) + \frac{\log_2\left[\frac{8\pi \mathrm{e} \cdot i \cdot n}{(1-i)^2}\right]}{2n} + O\left(n^{-2}\right).$$

Implication of the Theorem

- When an attacker faces a channel with synchronization errors its problem of cryptanalysis becomes more complex.
- Deliberate insertion of random bits into the cipher-text significantly enhances the cryptographic security.

Instead Conclusions

Bart Preneel, President of IACR

(International Association for Cryptologic Research):

Challenges for Crypto

- **security for 50-100 years**
- authenticated encryption of Terabit/s networks
- **ultra-low footprint / power / energy**
- secure software and hardware implementations
- performance
- **low-cost security**

Final Note

We need Synergy of Complementary Topics for Obtaining the Additional Value

(literally to achieve: 1 + 1 => 3)

Thank You Very Much for the Attention,

and

QUESTIONS Please!